DISCOVERY

Application of geo-electric indices in groundwater vulnerability mapping: A case study of Agbor, Delta State, southern region Nigeria

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To Cite:
Aghogho O, Ighrakpata F, Umayah OS. Application of geo-electric indices in groundwater vulnerability mapping: A case study of Agbor, Delta State, southern region Nigeria. *Discovery* 2023; 59: e51d1210

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Peer-Review History
Received: 27 March 2023
Reviewed & Revised: 31/March/2023 to 10/April/2023
Accepted: 14 April 2023
Published: May 2023

Peer-Review Model
External peer-review was done through double-blind method.

Discovery
pISSN 2278–5469; eISSN 2278–5450

DISCOVERY SCIENTIFIC SOCIETY

ABSTRACT

To identify the aquifer protection and groundwater potential of the aquifer in Agbor and its surroundings, Delta State, Nigeria, an electrical resistivity approach was used. The Schlumberger configuration was used to conduct a total of 16 vertical electrical soundings (VES) surveys. To process and interpret the VES data, a quantitative partial curve matching technique was used, which involved computer models and iterative software. Aquifer resistivity, aquifer thickness, aquifer conductivity and transverse resistivity, transmissivity are parameters that are estimated, with a value range from 205.3 to 3942.9Ωm, 17.3 to 36.4 m. 0.000253 to 0.004871, 1070.24 to 118681.3 and 173 to 364 m^2/day respectively. Results obtained from VES data suggested that the layer model ranges from 5 to 6 layers, it was observed that curve KHA is the dominant curve type with 44%, followed by HAA at 25%, while curve HKQH is 7%, HKH, KHAA, HAK and QHA are 6%. Findings from longitudinal conductance revealed that aquifer protective capacity ranges from weak to poor; this implies groundwater is prone to surface contamination. Deduction from this study suggested that the study is vulnerable to surface contamination due to anthropogenic activities.

Keywords: Vertical, conductance, array, resistivity, groundwater.

1. INTRODUCTION

Following Sustainable Development Goal (UN General Assembly 2015), freshwater is vital for human health and a country's development (i.e., ensuring availability and sustainable management of water and sanitation for all). With location and time, there are significant differences in the distribution of freshwater resources within a locality. Therefore, each alternate source of freshwater faces difficulties in gaining access (i.e., surface and groundwater). The southern part of Nigeria has been faced with water shortages over the past ten years, particularly at the height of the dry season (Eyankware and Ephraim, 2021; Ehirim and Nwankwo, 2010; George et al., 2015). This can occasionally result in

triggering numerous health problems (Eyankware and Aleke, 2021). Institutions and the inhabitant of the study area are faced with water shortages.

Recent anthropogenic activities have contaminated groundwater resources, which were once the source of the town's water supply. Because of this the inhabitant of the study area no longer relies on groundwater. Various fields of science have tried to solve water scarcity problems within the southern parts of Nigeria (Umuyah and Eyankware, 2022; Eyankware et al., 2022; Akinwumiju and Orimoogunje, 2012). The use of the geophysical approach has been more relevant in the determination of groundwater potential and in the evaluation of aquifer vulnerability across the globe (Ehirim and Nwankwo, 2010; George et al., 2015; Dan-Hassan and Olorunfemi, 1999; Ibuot et al., 2013; Nejad et al., 2011; Danielson et al., 2007). Other approaches like electromagnetic and electrical resistivity imaging were ruled out due to factors like restricted area and the settlement's dispersed layout. One of the most effective and affordable geophysical techniques for identifying possible groundwater zones is the electrical resistivity method. Numerous studies have documented the numerous applications of the resistivity method; it contrasts between rock strata with various electrical characteristics and delivers subsurface information with little to no environmental harm. In addition to mineral exploration, slide modeling, determining saltwater intrusion, determining environmental pollution and foundation engineering, the electrical resistivity method is used for groundwater prospecting (Olurunfemi et al., 2004). Several geoscientists have investigated the aquifer's susceptibility in Nigeria. Obiora et al., (2016) investigated the aquifer protection capabilities of Ezza North in the Nigerian state of Ebonyi.

According to their research, regions with high aquifer yield also tend to have high transverse resistance values and regions with superior aquifer protective capacity can be ascribed to argillaceous clay materials that are found on top of soil that has a range of moderate to high aquifer potential. The Dar Zarrouk parameter was used to assess the aquifer vulnerability and potential of the Ikwo and Ezza area in the Ebonyi state of Nigeria. They found that the aquifer protective capacity of the area is regarded as average and that the aquifer potential is influenced by the underlying geology. In their evaluation of a sub-urban area's aquifer potential and vulnerability in Cross River State, southeast Nigeria, Eyankware and Umayah, (2022) found that the area covered in shale and clay was deemed to have a high aquifer protective capacity when compared to other areas of the research area. There has been little to no research done to determine the groundwater potential and protective capacity of aquifers in Agbor and its adjacent areas, despite the fact that the protective capacity of aquifers has been analyzed using geophysical methods in other sections of the Niger Delta.

Determining the potential for groundwater and the capacity to protect the aquifer in the Agbor area of Delta State, therefore, requires a thorough study. The purpose of the study is to determine the groundwater potential and aquifer protective capacity of the study region using secondary geoelectric parameters (Dar Zarrouk parameters) and to give a general outline of the groundwater potential area.

Location, accessibility, topography and climate

The study was carried out in Agbor town, which is located in Delta State's Ika South Local Government Area, Nigeria. It lies within longitudes 6°05′ E and 6°20′ E and latitudes 6°07′ N and 6°25′ N. The area lies within the equatorial climate with two distinct seasons; the wet (April to September) and dry (October to March) seasons; high humidity and atmospheric temperature of between 24°C – 27°C support the rainforest vegetation (Iloeje, 1981; Olobaniyi et al., 2007; Odjugo, 2008; Eyankware and Ephraim, 2021). The area lies within the subequatorial climate, with annual rainfall over 2000mm, a long-wet season (about 8 months) and high humidity, which supports the rainforest-type vegetation. It has a population above 240,000 people and is located along a major route connecting southeastern and northwestern Nigeria. Consequently, it is a flourishing center of trade and agriculture. The physiography of the area shows two topographic highs separated by a valley. Within the valley is River Asimiri, which flows in a southwest-northeast direction (Figure 1).

The Bini formation is a classic example of the recent tertiary sedimentary sandstone that dominates the region's geology. Its texture is made up of fine to coarse reddish (iron, haematite) sediments, which give the sandstone a porous quality. This suggests that leachate (such as iron) could easily enter the groundwater in the underlying aquifer. With an annual mean air temperature of 27.0 °C, the climate in the study region exhibits the traits of a sub-equatorial climate. (Odjugo, 2008). With a mean annual rainfall of 2,255 mm, the rainfall pattern is two peaks or maximal. The soil type is red-yellow ferralsols and the average relative humidity is 81% (Avwunudiogba, 2000).

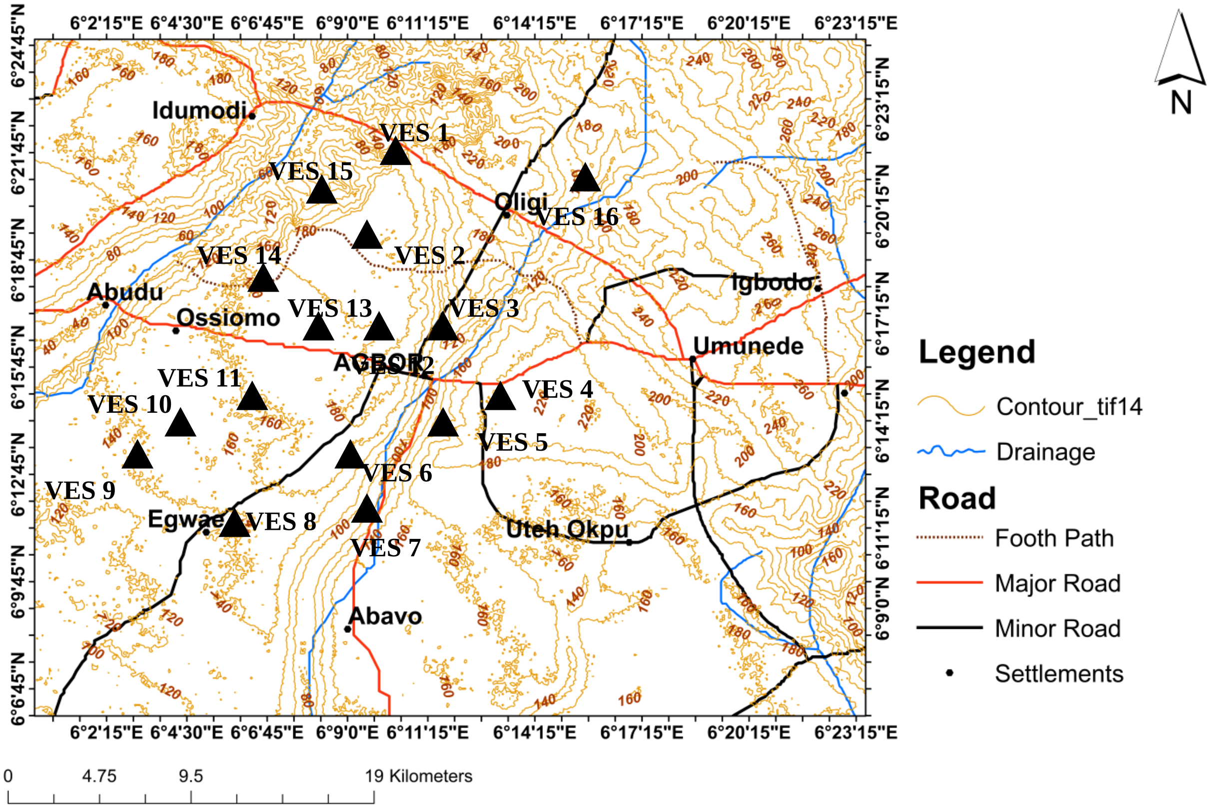

Figure 1 Topographic map of study area showing VES POINTS

Geology and hydrogeology

The underlying geology of Agbor indicates that it is a component of the Benin formation, which is covered by lateritic soil for the first few meters and fine-grained sand that varies in thickness from 9 to 58 meters. The primary aquifer is composed of a variety of horizons of intercalated discontinuous lenses of clay in a sequence of medium to coarse-grained sands that are beneath the fine-grained sands. The presence of groundwater occurs primarily in open spaces at depths typically more than 60 m. According to inferences made from groundwater level contouring, the area's principal river, the Orogodo, receives a portion of its replenishment from the aquifer (Nwajide, 2006; Olobaniyi et al., 2007; Akpoborie et al., 2011).

2. METHODOLOGY

The VES method was used in this investigation to identify prospective groundwater-bearing zones and the aquifer's susceptibility to surface contamination. In the study region, as in Figure 3, sixteen (16) VES were conducted using the ABEM Terrameter SAS1000 and its accessories. For each VES profile, a Schlumberger electrode array was used, with a maximum half current (AB/2) electrode spacing of 200 m and a maximum half potential (MN/2) electrode separation of 10 m. Surfer software was used to model the spatial distribution of S, Tr, L, pt, aquifer thickness, resistivity, conductivity and ISO-resistivity contour maps at intervals of AB/2 from 6 m to 150 m. The VES method was used in this investigation to identify prospective groundwater-bearing zones and the aquifer's susceptibility to surface contamination.

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$$\rho a = \pi \left(\frac{\left(\frac{AB}{2}\right) - \left(\frac{MN}{2}\right)}{MN} \right) \Delta V / I \quad (1)$$

The geoelectrical curves were produced by plotting the apparent resistivity data against the current electrode spacing (AB/2). The adoption of the IX1D software, which made it possible to create sound curves, has improved the processing of the data. The thickness of the aquifer was determined from the drawn geoelectrical sections using the sounding curve data as input. Using the charts provided by Loke (1999) and Kearey, Brooks and Hills, lithologies that fit the geoelectric section were determined (2002). Some variables associated with the various combinations of the thickness and resistivity of the geoelectric layer are essential for the research and understanding of the geologic model. Those parameters are Dar Zarrouk: Longitudinal (S) and transverse (T), respectively, given by

$$S = \frac{h}{p} \quad (2)$$

$$T = hp \quad (3)$$

1. The total Longitudinal Unit Conductance (S) was calculated using the formula given below

For 'n' layers, the total longitudinal conductance is

$$S = \sum_{i=1}^{n} \frac{h_i}{\rho_i} = \frac{h_i}{\rho_i} + \frac{h_2}{\rho_2} + \cdots + \frac{h_n}{\rho_n} \quad (4)$$

as proposed by Eyankware et al., (2022)

Equation is used to get the Transverse Resistance for a given VES curve.

The transverse resistance is

$$\rho_t = \frac{T}{H} = \frac{\sum_{i=1}^{n} h_i \rho_i}{\sum_{i=1}^{n} h_I} \quad (5)$$

as proposed by Eyankware et al., *(2021)*

Transmissivity (T) is the product of the hydraulic conductivity (k) and the aquifer layer thickness.

$$T = K \times h \quad (6)$$

3. RESULT AND DISCUSSION

In Agbor-Obi, a geoelectric investigation was conducted. In the study region, 16 VES were recorded. The result of the resistivity survey shows the geoelectric parameters of the sixteen vertical electrical soundings presented (Table 1).

Table 1 Geoelectric parameter and lithologic delineation VES at Agbor-Obi Area

S/N	Layers	Resistivity	Thickness	Depth	Lithology	Curves
VES 1	1	190.2	0.8	0.8	Lateritic Topsoil	HKQH $\rho_1 > \rho_2 < \rho_3 > \rho_4 > \rho_5 < \rho_6$
	2	83.0	3.6	4.5	Sandy Clay	
	3	379.6	10.4	14.9	Fine to Medium sand	
	4	167.2	12.7	27.6	Medium Sand	
	5	74.0	26.9	54.5	Medium to Coarse Sand	
	6	584.3	---	---	Coarse Sand	
VES 2	1	261.7	1.7	1.7	Lateritic Topsoil	HKH $\rho_1 > \rho_2 < \rho_3 > \rho_2 < \rho_3$
	2	127.3	7.6	9.4	Clayey	
	3	436.6	26.8	36.2	Fine to Medium sand	
	4	298.8	30.1	66.3	Medium to Coarse Sand	
	5	3942.9	---	---	Coarse Sand	

VES 3	1	648.9	0.9	0.9	Lateritic Topsoil	KHA $\rho_1 < \rho_2 > \rho_3 < \rho_4 < \rho_5$
	2	216.9	7.6	8.5	Clayey Sand	
	3	742.3	14.2	22.7	Fine to Medium sand	
	4	1941.7	17.3	40.0	Medium to coarse Sand	
	5	3849.8	---	---	Coarse Sand	
VES 4	1	209.8	1.4	1.4	Lateritic Topsoil	HAA $\rho_1 > \rho_2 < \rho_3 < \rho_4 < \rho_5$
	2	72.9	4.5	6.0	Clayey Sand	
	3	370.9	37.1	43.1	Fine to Medium sand	
	4	464.1	25.2	68.3	Medium to Coarse Sand	
	5	555.7	---	---	Coarse Sand	
VES 5	1	286.4	1.1	1.1	Lateritic Topsoil	HAA $\rho_1 > \rho_2 < \rho_3 < \rho_4 < \rho_5$
	2	142.1	5.1	6.2	Clayey Sand	
	3	337.7	19.8	26.0	Fine to Medium sand	
	4	668.4	19.0	45.0	Medium Sand	
	5	4509.4	---	---	Coarse Sand	
VES 6	1	359.3	1.0	1.0	Lateritic Topsoil	HAA $\rho_1 > \rho_2 < \rho_3 < \rho_4 < \rho_5$
	2	250.6	7.8	8.8	Clayey Sand	
	3	359.8	13.2	21.9	Fine to Medium sand	
	4	1075.2	19.2	41.1	Medium Sand	
	5	2199.3	---	---	Coarse Sand	
VES 7	1	651.9	1.2	1.2	Lateritic Topsoil	QHA $\rho_1 > \rho_2 > \rho_3 < \rho_4 < \rho_5$
	2	308.9	9.3	10.5	Clayey Sand	
	3	230.0	18.9	29.4	Fine to Medium sand	
	4	731.4	19.0	48.4	Medium Sand	
	5	2099.3	---	---	Medium to Coarse Sand	
VES 8	1	126.7	0.7	0.7	Lateritic Topsoil	KHA $\rho_1 < \rho_2 > \rho_3 < \rho_4 < \rho_5$
	2	266.5	4.3	5.0	Clayey Sand	
	3	136.4	26.8	31.8	Fine to Medium sand	
	4	345.2	31.2	63.0	Medium Sand	
	5	1243.6	---	---	Medium to Coarse Sand	
VES 9	1	141.0	1.0	1.0	Lateritic Topsoil	KHA $\rho_1 < \rho_2 > \rho_3 < \rho_4 < \rho_5$
	2	279.4	7.2	8.2	Clayey Sand	
	3	130.0	14.3	22.5	Fine to Medium sand	
	4	360.8	18.9	41.3	Medium Sand	
	5	520.5	---	---	Medium to Coarse Sand	
VES 10	1	88.4	1.1	1.1	Lateritic Topsoil	KHA $\rho_1 < \rho_2 > \rho_3 < \rho_4 < \rho_5$
	2	183.0	9.9	11.1	Clayey Sand	
	3	98.1	16.2	27.3	Fine to Medium sand	
	4	205.3	19.8	47.1	Medium Sand	
	5	457.8	---	---	Medium to Coarse Sand	
VES 11	1	131.2	1.2	1.2	Lateritic Topsoil	KHA $\rho_1 < \rho_2 > \rho_3 < \rho_4 < \rho_5$
	2	272.5	6.7	7.9	Clayey Sand	
	3	581.8	19.7	27.6	Fine to Medium sand	
	4	141.6	36.4	64.0	Medium Sand	
	5	2496.0	---	---	Coarse Sand	
VES 12	1	63.6	0.8	0.8	Lateritic Topsoil	KHAA $\rho_1 < \rho_2 > \rho_3 < \rho_4 < \rho_5 < \rho_6$
	2	224.8	3.1	3.9	Clayey Sand	
	3	37.4	8.6	12.4	Fine to Medium sand	

	4	358.0	11.8	24.2	Medium Sand	
	5	605.6	18.0	42.2	Medium to Coarse Sand	
	6	610.0	---	---	Coarse Sand	
VES 13	1	150.3	1.4	1.4	Lateritic Topsoil	KHA $\rho_1 < \rho_2 > \rho_3 < \rho_4 < \rho_5$
	2	403.2	10.2	11.5	Clayey Sand	
	3	197.2	32.4	43.9	Fine to Medium sand	
	4	702.0	20.0	63.9	Medium Sand	
	5	3432.5	---	---	Coarse Sand	
VES 14	1	1022.5	1.2	1.2	Lateritic Topsoil	HAK $\rho_1 > \rho_2 < \rho_3 < \rho_4 > \rho_5$
	2	434.7	6.2	7.3	Clayey Sand	
	3	2644.7	13.3	20.7	Fine to Medium sand	
	4	3500.1	21.9	42.5	Medium Sand	
	5	1162.4	---	---	Medium to Coarse Sand	
VES 15	1	163.0	1.1	1.1`	Lateritic Topsoil	KHA $\rho_1 < \rho_2 > \rho_3 < \rho_4 < \rho_5$
	2	428.1	9.6	7.3	Clayey Sand	
	3	209.8	19.6	20.7	Fine to Medium sand	
	4	700.8	18.4	42.5	Medium Sand	
	5	211.7	---	---	Medium to Coarse Sand	
VES 16	1	403.3	0.7	0.7	Lateritic Topsoil	HAA $\rho_1 > \rho_2 < \rho_3 < \rho_4 < \rho_5$
	2	234.5	9.3	10.7	Clayey Sand	
	3	261.9	19.1	29.1	Fine to Medium sand	
	4	533.8	19.4	48.5	Medium Sand	
	5	1699.1	---	---	Medium to Coarse Sand	

Table 2 Dar Zarrouk Parameter Obtained from the Iterated Field Data at Agbor-Obi Area

S/N	Aquifer Resistivity ρ	Aquifer Thickness H	Aquifer Conductivity $\sigma = \frac{1}{\rho}$	Longitudinal Conductance $S = \sigma \times h$	Transverse Resistivity $R = h\rho$	Transmissivity $T_r = kh$
VES 1	740.0	26.9	0.001351	0.036342	19906.00	269
VES 2	3942.9	30.1	0.000253	0.007165	118681.29	301
VES 3	1941.7	17.3	0.000515	0.008910	35391.41	173
VES 4	464.1	25.2	0.002155	0.054306	11695.32	252
VES 5	668.4	19.0	0.001496	0.028424	12699.60	190
VES 6	1075.2	19.2	0.000930	0.017856	20643.84	192
VES 7	731.4	19.0	0.001367	0.025973	13896.60	190
VES 8	345.2	31.2	0.002897	0.090386	1070.24	312
VES 9	360.8	18.9	0.002772	0.052391	6819.12	189
VES 10	205.3	19.8	0.004871	0.096446	4064.94	198
VES 11	1416.0	36.4	0.000706	0.025698	51542.40	364
VES 12	605.6	18.0	0.001651	0.029718	10900.80	180
VES 13	702.0	20.0	0.001425	0.028500	14040.00	200
VES 14	3500.1	21.9	0.000286	0.006362	76652.19	219
VES 15	700.8	18.4	0.001427	0.026256	12894.72	184
VES 16	533.8	19.4	0.001873	0.036336	10355.72	194
Min.	205.3	17.3	0.000253	0.006362	1070.24	173
Max.	3942.9	36.4	0.004871	0.096446	118681.3	364
Aver.	1226.75	23.0222	0.001728	0.037438	30055.87	230.222

Description of Vertical Electrical sounding

In Figure 2a to 2g and Table 1, the result reveals five to six separate strata. The study area's lithology has been defined as including lateritic topsoil, sandy clay and fine to medium-grained, medium to coarse and coarse sand. The topsoil is laterite with resistivity ranging from 63.6 to 1022.5Ωm and thickness varying from 0.7 to 1.7m. The second layer is sandy clay with resistivity ranging from 72.9 to 434.7Ωm and thickness varying from 3.1 to 10.2m. The third layer where the aquifer is located is fine to medium sand with resistivity ranging from 37.4 to 2644.1Ωm and thickness varying from 10.4 to 37.1m. The fourth layer is medium to coarse sand with resistivity ranging from 141.6 to 3500.1Ωm and thickness varying from 11.8 to 31.2m. The fifth layer is medium to coarse sand with resistivity ranging from 457.8 to 4508.4Ωm. The thickness of this varies from 18.0 to 26.9. Medium to coarse sand in the sixth layer has a resistivity of between 584 and 610.0 m. The thickness of the layer cannot be determined as the current electrode terminated in this layer. The low resistivity encounter in the third layer is as a result of thin lens of clay present in this layer.

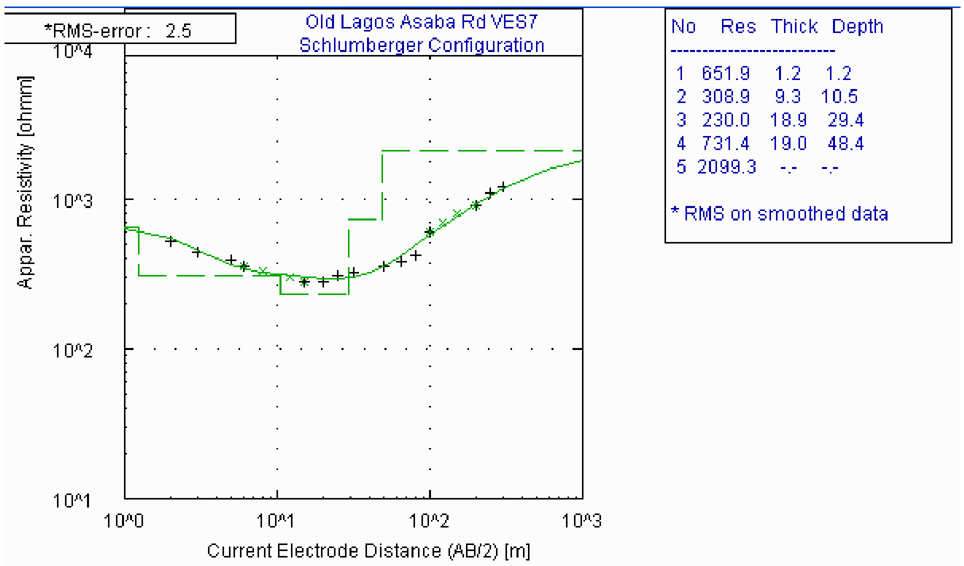

Figure 2a Sounding Curve for Agbor-Obi Hydro geophysical Investigation of VES 7

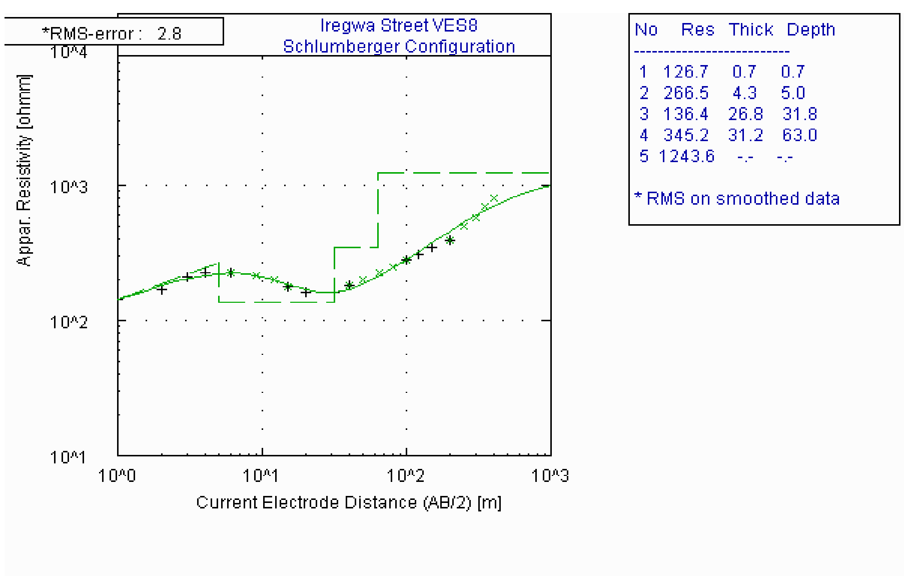

Figure 2b Sounding Curve for Agbor-Obi Hydro geophysical Investigation of VES 8

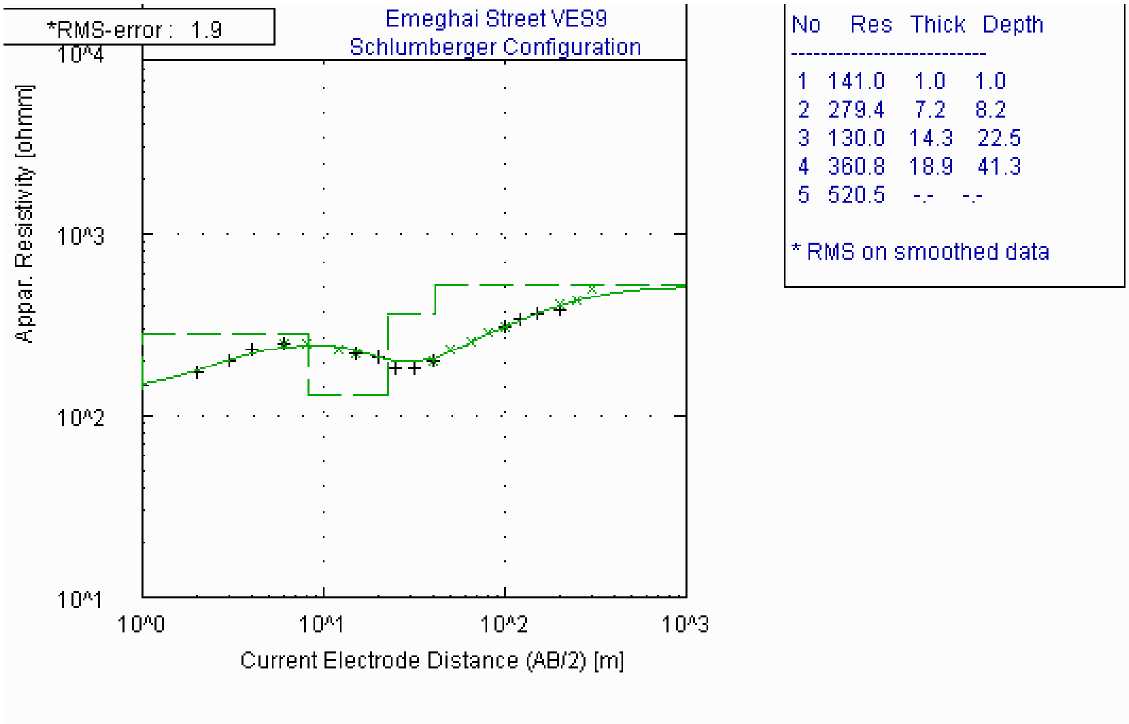

Figure 2c Sounding Curve for Agbor-Obi Hydro geophysical Investigation of VES 9

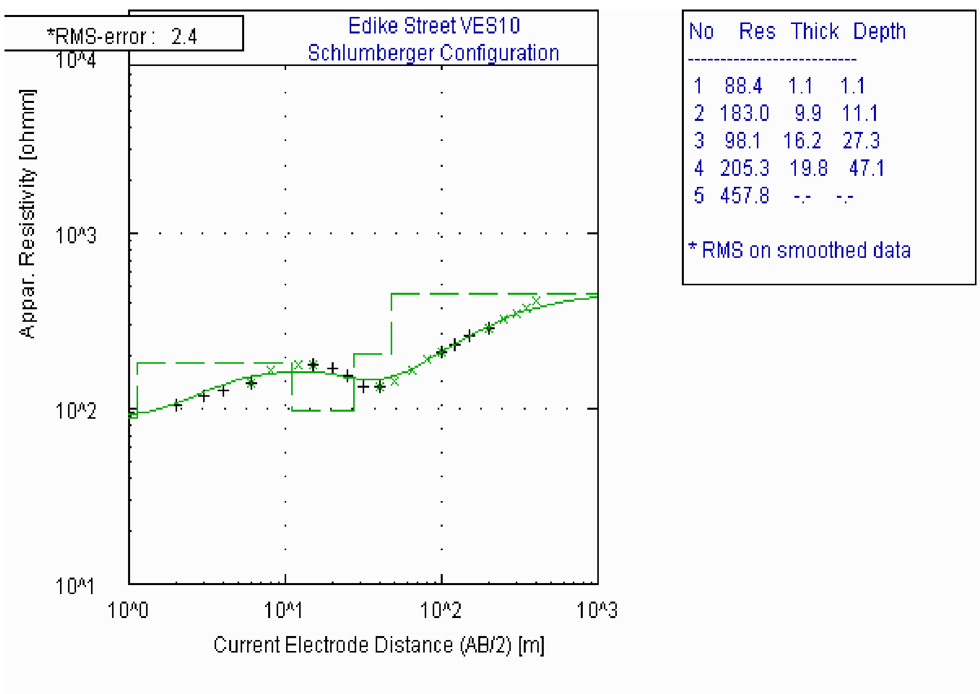

Figure 2d Typical Sounding Curve for Agbor-Obi Hydro geophysical Investigation of VES 10

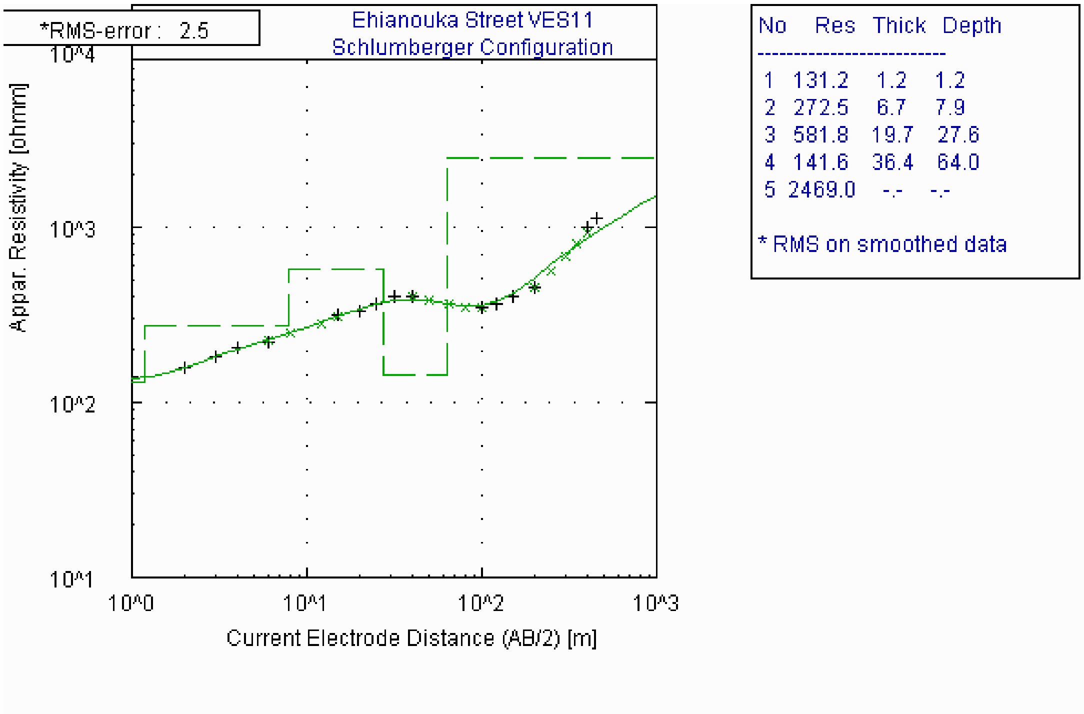

Figure 2e Sounding Curve for Agbor-Obi Hydro geophysical Investigation of VES 11

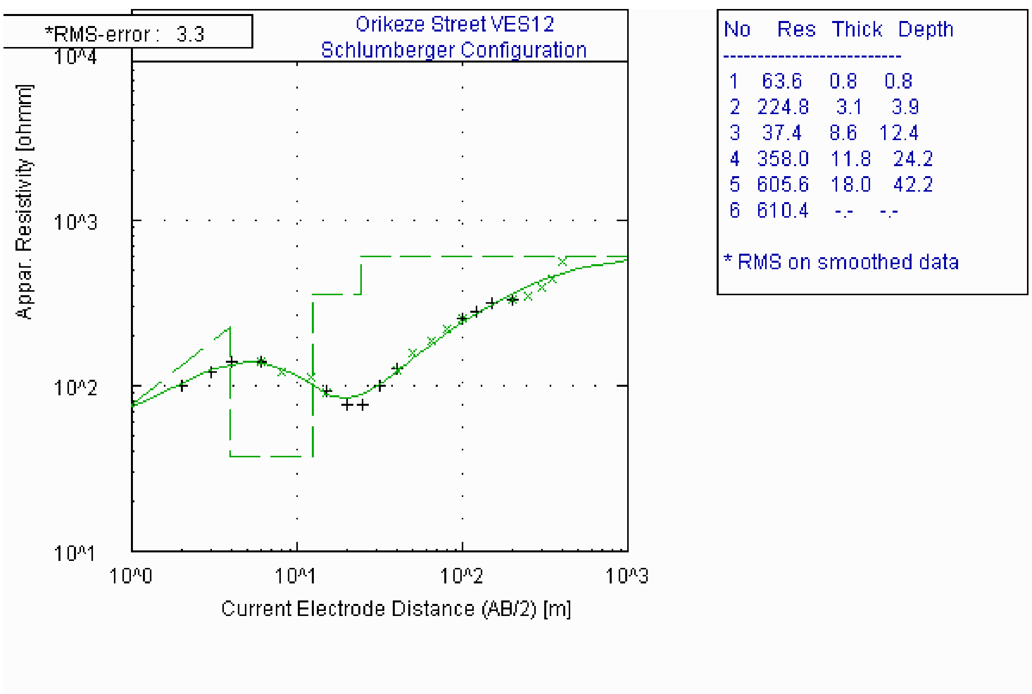

Figure 2f Typical Sounding Curve for Agbor-Obi Hydro geophysical Investigation of VES 12

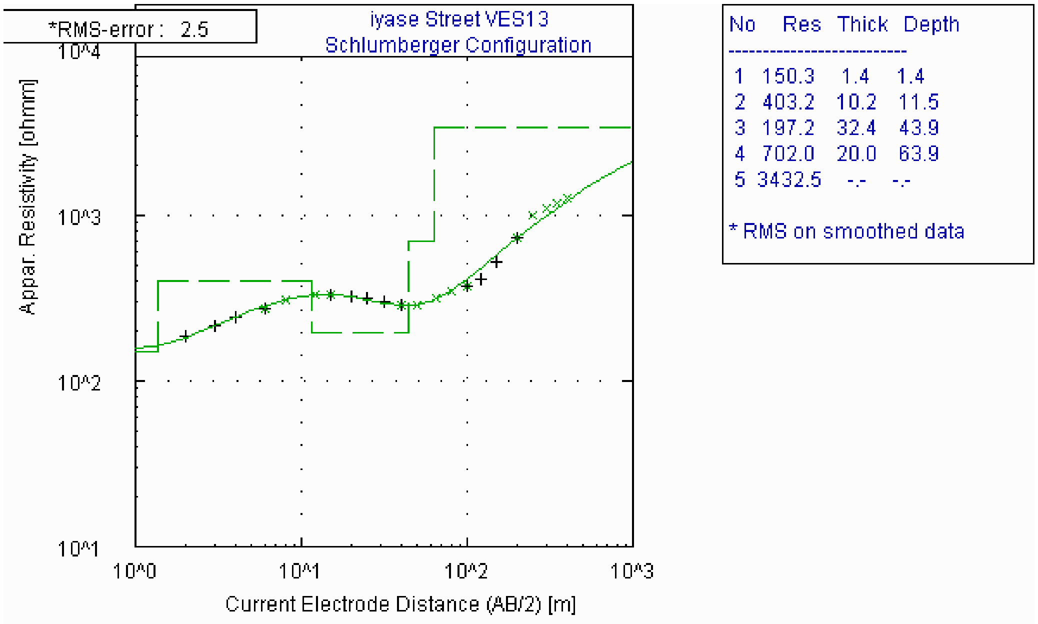

Figure 2g Typical Sounding Curve for Agbor-Obi Hydro geophysical Investigation of VES 13

Spatial variation of aquifer geometric properties

Aquifer Resistivity

Aquifer resistivity ranges from 205.3 to 3942.9 Ωm, with the highest resistivity value of 3942.9 Ωm seen in VES 2 and the least aquifer resistivity value of 205.3 Ωm at VES 10 (Table 2). Findings from Figure 3 suggested that the area with red color with a resistivity range of 320 to 350 Ωm has a high aquifer resistivity value. While the area with purple color has the least resistivity value with a value range of 190 to 200 Ωm. Further findings revealed that the area with yellow color has aquifer resistivity value of 270 to 310 Ωm (Figure 3).

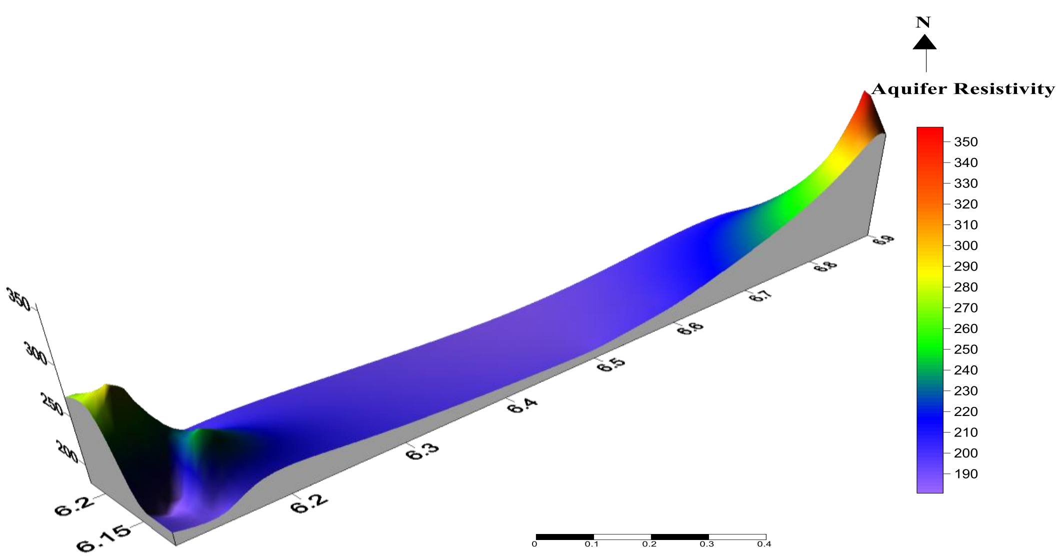

Figure 3 Spatial distribution of aquifer resistivity in 3D

Aquifer thickness

Table 2 shows that the aquifer's thickness at VES3 and VES11, respectively, spans from 17.3 to 36.4 m, with an average value of 23 m. When compared to other areas in the research region, the northeastern portion of the study area has a thicker aquifer (Figure 4).

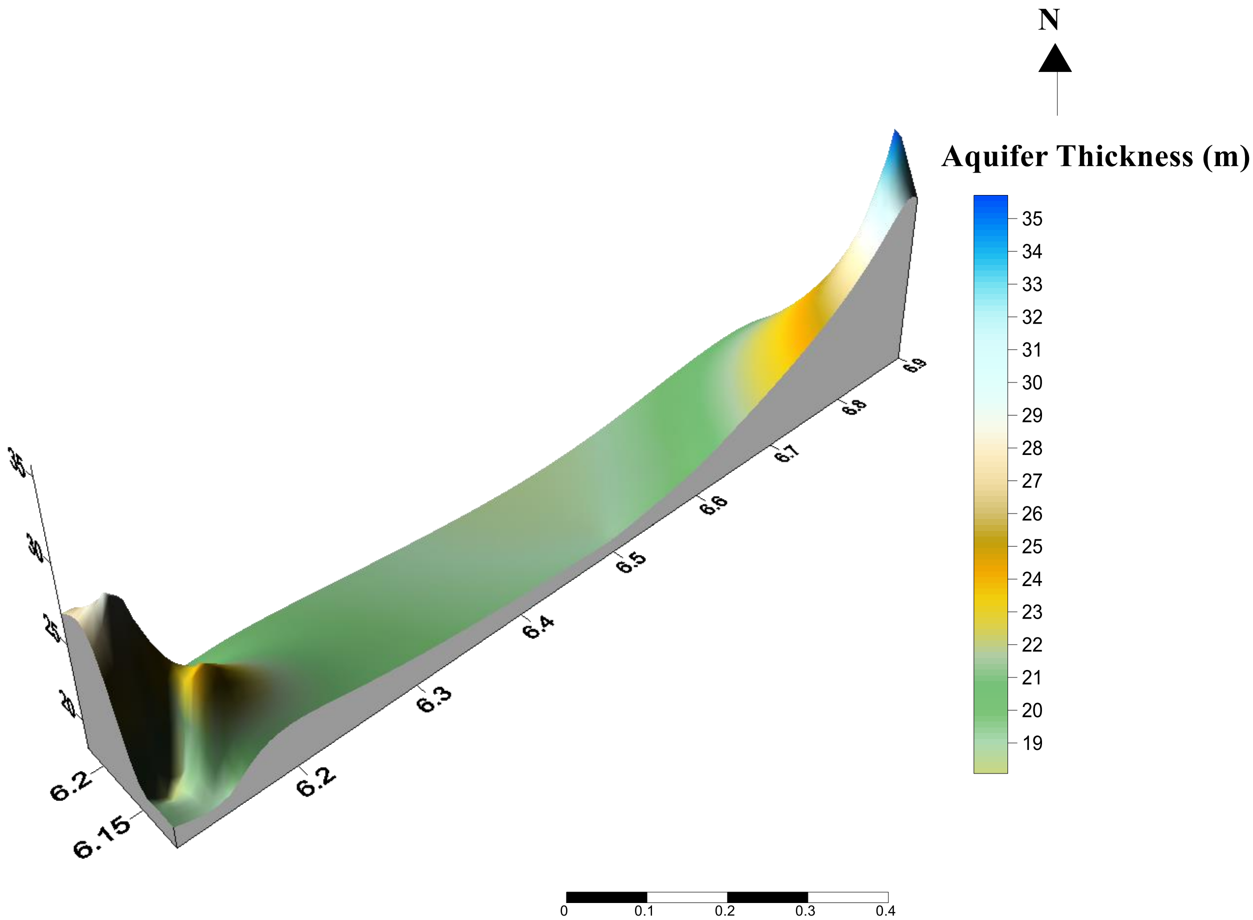

Figure 4 Spatial distribution of aquifer thickness in 3D

Aquifer vulnerability

The propensity or likelihood that an aquifer system is susceptible to surface contamination is known as aquifer vulnerability. Aquifer vulnerability is a quantity that indicates the likelihood that contamination will happen or not, rather than being a quantity that can be measured. As a result, it is reliant on a few quantifiable factors. In this work, the aquifer potential and groundwater vulnerability were assessed using the longitudinal conductance (S) and transverse unit resistance (Tr) values that were generated from the basic geoelectrical characteristics of the geoelectric layers.

Longitudinal conductance

The degree of protection provided by an earth medium is indicated by how well it filters and slows percolating. (Dan-Hassan and Olorunfemi, 1999). This measure shows how susceptible the aquifer is to contamination. A region's capacity to defend itself is increased by the height of an over burden unit of a geological formation, such as clay, shale or compact sandstone (Henriet, 1976). The longitudinal conductance values obtained from the iterated (Table 4, 5) shows that the study area is not protected since majority of the protective capacity rating is poor (<0.1) in all the parts of the study area. Since there isn't much clay in the research area as an overburden impermeable material, the protective capacity is minimal, which facilitates the percolation of contaminants into the aquifer. The aquifer in study area is therefore prone to contamination from potential contaminant but due to the fact that the water table is very far from the surface, this will take the contaminant long time to get to the aquifer thereby making the groundwater suitable for use. Deduction from Table 2, suggested that the lowest longitudinal conductance value of 0.006362 was observed at VES 14 while the highest longitudinal conductance value of 0.096446 was observed at VES 10, with average longitudinal conductance value of 0.037438 (Figure 5) (Table 2). The research area's aquifer protection capability is deemed to be weak and inadequate, according to further deduction from (Table 3). Hence one could say aquifer within the study area is prone to surface contamination. The results of this study are consistent with those of Umayah and Eyankware, (2022), which found that some Niger Delta aquifers are marginally susceptible to surface contamination.

Table 3 Results of longitudinal conductivity

S/N	Longitudinal Conductivity of Protecting Layers	Protective Capacity Rating
VES 1	0.102890	Weak
VES 2	0.0570795	Poor
VES 3	0.008232	Poor
VES 4	0.055682	Poor
VES 5	0.0316975	Poor
VES 6	0.022113	Poor
VES 7	0.035025	Poor
VES 8	0.077131	Poor
VES 9	0.048811	Poor
VES 10	0.082031	Poor
VES 11	0.081164	Poor
VES 12	0.079750	Poor
VES 13	0.056685	Poor
VES 14	0.006681	Poor
VES 15	0.037213	Poor
VES 16	0.0037667	Poor
Minimum	0.003767	
Maximum	0.10289	
Average	0.049589	

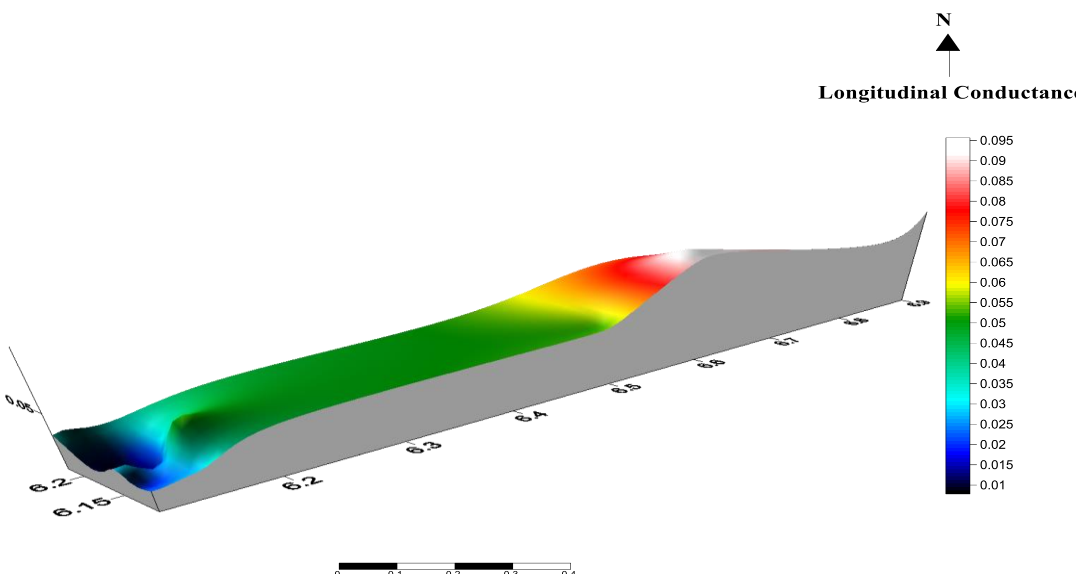

Figure 5 Three-dimensional spatial distribution of longitudinal conductance

Transverse resistivity (ρt)

Henriet, (1979), empirical basics, it can be admitted that ϱt is directly proportional to transmissivity. Eyankware et al., (2022) and Eyankware and Aleke, (2021) further pointed out that ϱt is used to determine zone of high groundwater potentials and areas suitable for drilling. Transverse resistivity 4064.94 to 118681Ω. The value obtained for the groundwater quality varies from 0.00253 to 0.04871. It was also observed that the highest ϱt of 118681.29 was observed at VES2 and the least value of 1070.24 at VES 8.

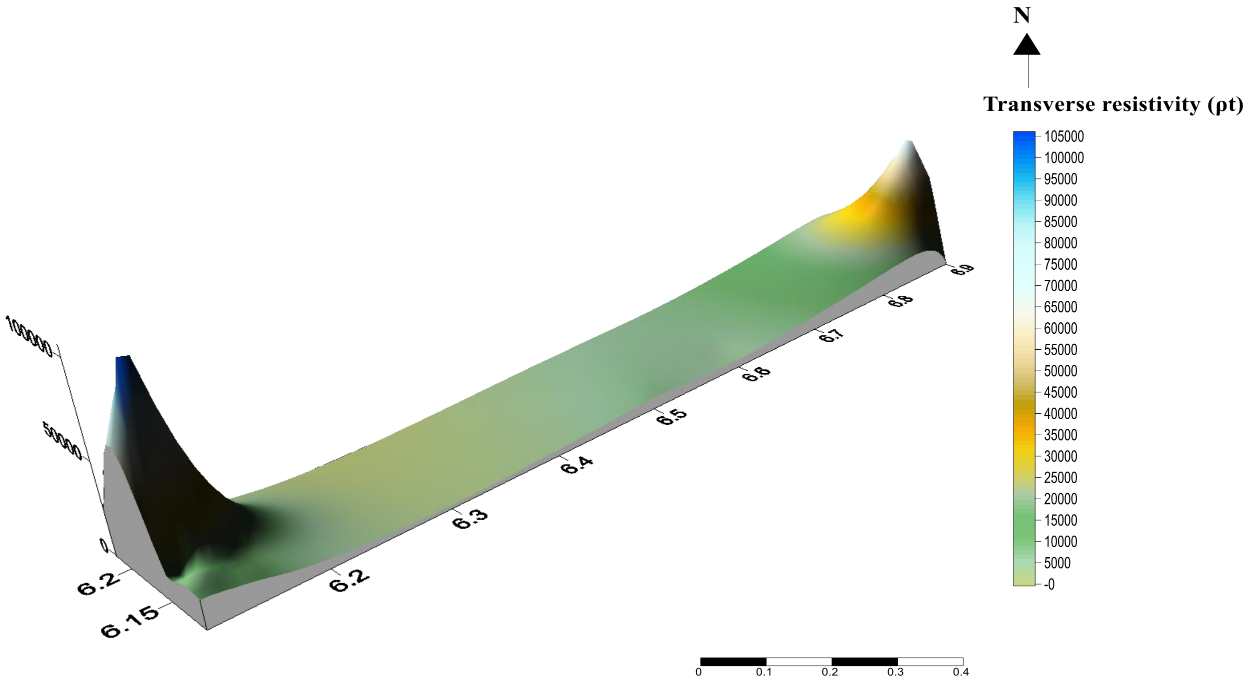

Figure 6 Spatial distribution of transverse resistivity in 3D

Transmissivity (T)

An aquifer's transmissivity refers to its capacity to transport groundwater throughout the entirety of its saturated thickness. Transmissivity is the highest groundwater flow rate attainable through a section of an aquifer with a unit width and a unit hydraulic gradient. T values range from 173 to 364 m^2/day with an average of 230.22 m^2/day.

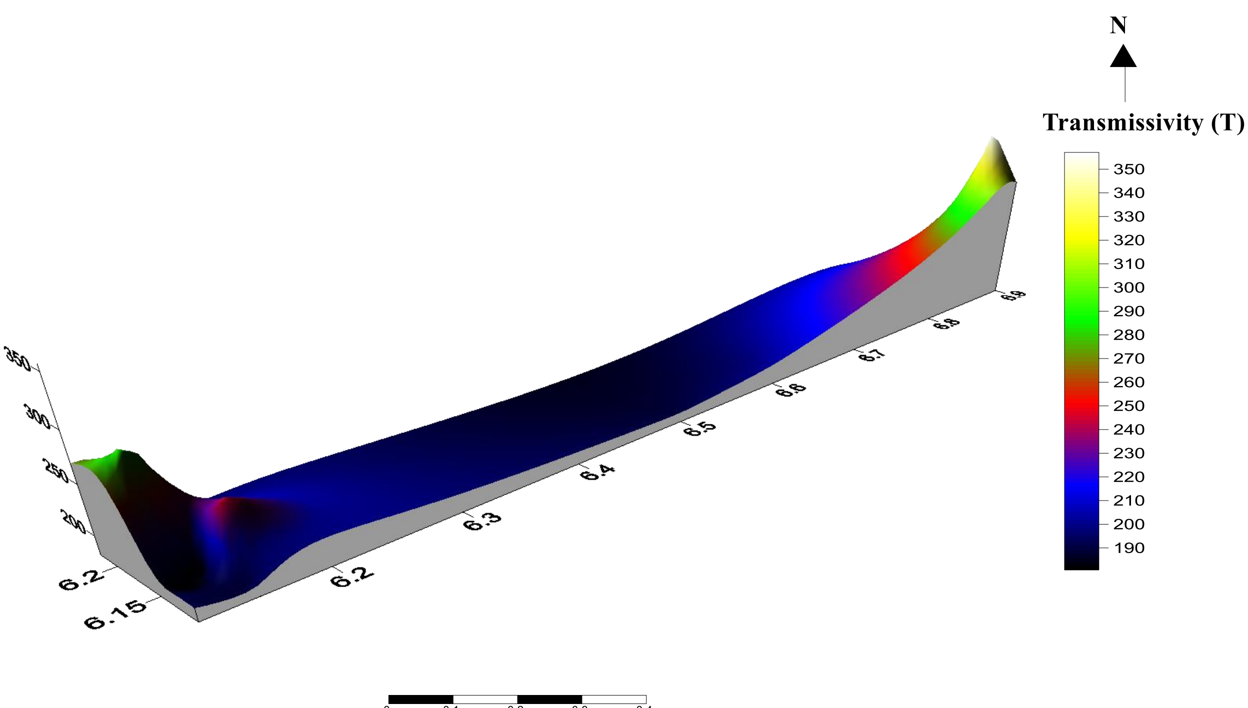

Figure 7 Spatial distribution of transmissivity in 3D

Aquifer Conductivity

According to the local variation map of aquifer conductivity in Figure 8, red and white hues with resistivity values between 0.0034 and 0.0046 were associated with relatively high aquifer conductivity. According to Figure 8, the relatively low aquifer conductivity

ranged from 0.0004 to 0.0012 and was colored pink. According to Obiora the area with low resistivity tends to have high conductive geo-material and as such poor groundwater quality.

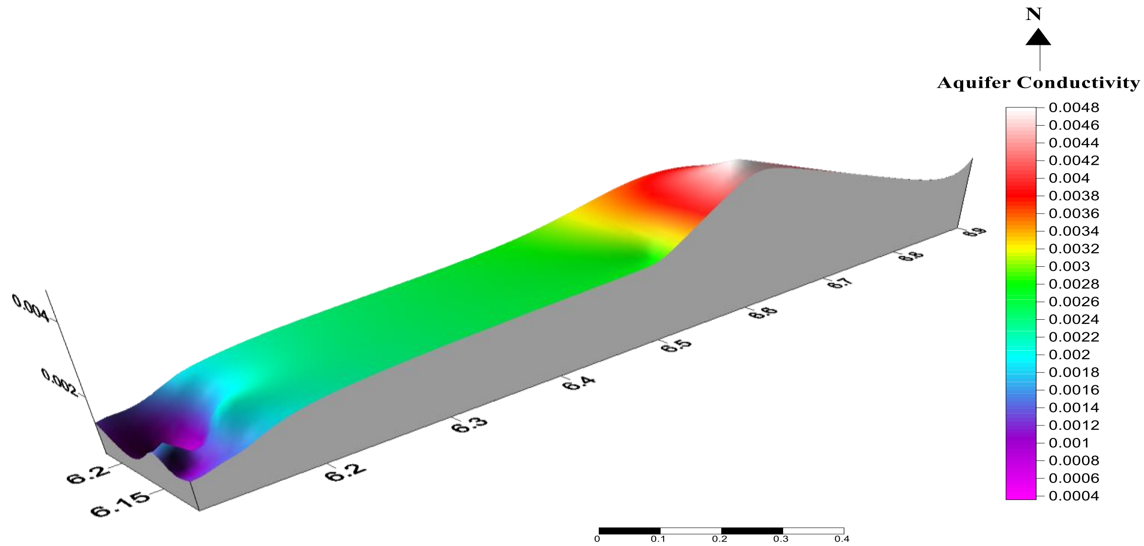

Figure 8 Spatial distribution of aquifer conductivity in 3D

Distribution of curve type

The research region has six different types of curves, including the HKQH, HKH, KHA, HAA, QHA, KHAA, HAK and HAA curves, according to deductions from VES. The H curve is the most common type of curve inside the Niger Delta region of Nigeria, according to a similar study conducted (Eyankware and Umuyah, 2022). The dominant curve in the area under study was discovered to be curve H. According to Umayah and Eyankware, (2022), the research area's heterogeneous geology could be the cause of the difference in curve type. The KHA curve accounted for 44% of all curve types, followed by the HAA curve with 25%, the QHA curve type with 7% and the HKH, HAA, KHA and HAK curve types with 6% each.

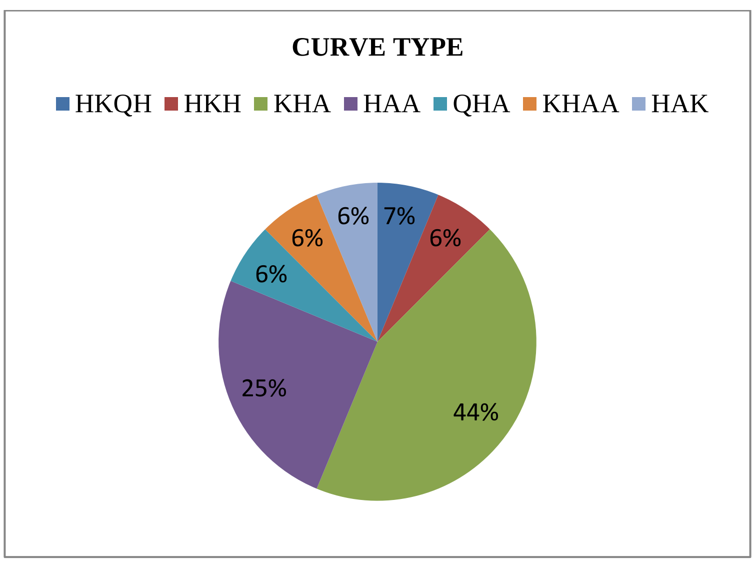

Figure 9 Pie chart presentation of curve type within the study

4. CONCLUSION

Detailed geophysical investigation was carried out within the study area. Sixteen vertical electrical soundings were obtained in the study area. The lithology identified in the study area consists of lateritic topsoil, sandy clay and fine to medium-grained, medium to coarse and coarse sand. The data were examined to identify the aquifer protection of the study area and the result reveals five to six distinct layers. Generally, longitudinal conductance is a measure of aquifer protective capacity ratings. The longitudinal conductance results from this investigation indicate that the studied area is vulnerable to surface pollution. The low value of the

protective capacity is a result of the absence significant amount of clay as an overburdened impermeable material in the study area thereby enhancing the percolation of contaminants into the aquifer.

Informed consent
Not applicable.

Ethical approval
Not applicable.

Conflicts of interests
The authors declare that there are no conflicts of interests.

Funding
The study has not received any external funding.

Data and materials availability
All data associated with this study are present in the paper.

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